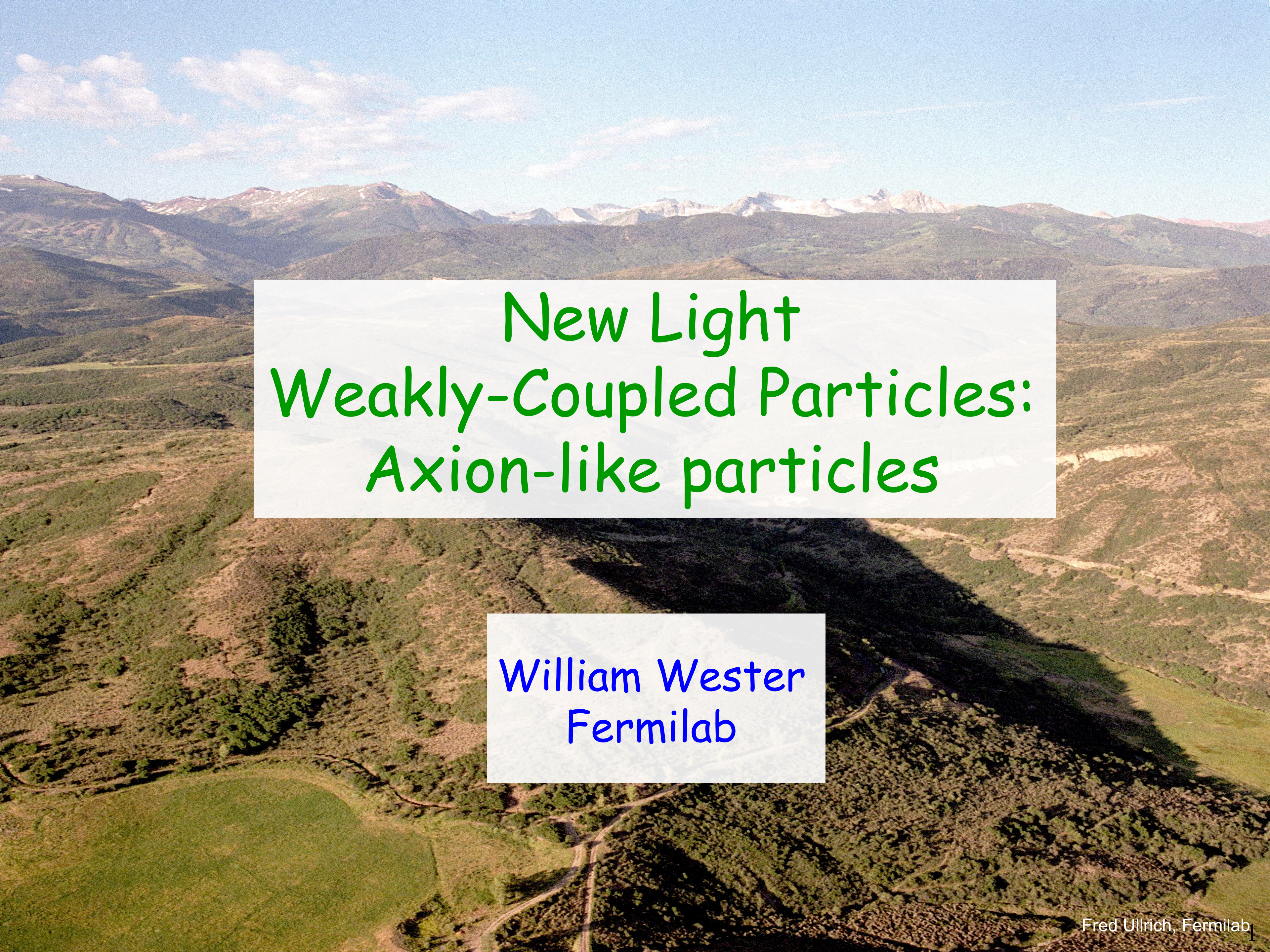
New Light Weakly-Coupled Particles: Axion-like particles

William Wester
Fermilab



Fred Ullrich, Fermilab

NLWCP

New: New Physics … potentially revolutionary in our understanding of matter, space, and time

Light: low mass possibly related to symmetries and experimentally accessible through direct production

Weakly-Coupled: implies perhaps a very high energy scale is involved and intensity experiments might be required to see rare processes

Particles: many possibilities

sub-GeV dark matter
axions
A' (A-prime)
WISPs
milli-charged particles
hidden photons
sterile neutrinos
axion-like particles
chameleons

Strong overlap with CF-3: Non-WIMP Dark Matter

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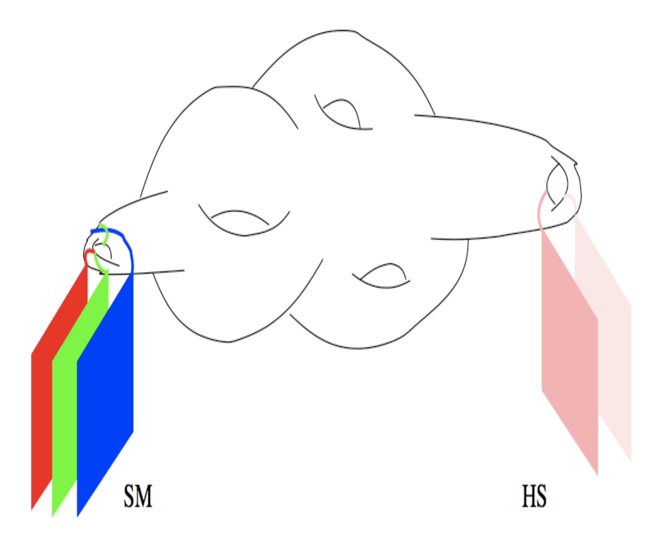
Portals connecting to the SM

Higgs Portal	$\epsilon_h \, \lvert h \rvert^2 \lvert \phi \rvert^2$
Neutrino Portal	$\epsilon_\nu \, (hL)\psi$
Vector Portal	$\frac{1}{2}\epsilon_Y \, F^Y_{\mu\nu} F'^{\mu\nu}$
Axion Portal	$\frac{1}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

Philip Schuster



Low mass scalars (pseudo-scalars) arise in many theoretical models (for example, modui in string theory, symmetry breaking at high scales, etc.)

Axions

- Postulated in the late 1970s as a consequence of not observing CP violation in the strong interaction.

$$L_{CP} = -\frac{\alpha_s}{8\pi}\underbrace{(\Theta - \arg\det M_q)}_{0 \le \overline{\Theta} \le 2\pi} \mathrm{Tr}\, \tilde{G}_{\mu\nu} G^{\mu\nu}$$

Raffelt

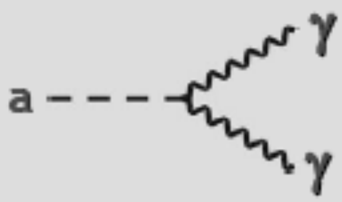
- The measurement of the electric dipole of the neutron implies $\overline{\Theta} < \sim 10^{-10}$. => Strong CP Problem of QCD
  - This is very much on the same order of an issue with the Standard Model as the hierarchy problem that motivates supersymmetry.
  - Axions originate from a new symmetry that explains small $\overline{\Theta}$

Bjorken “Axions are just as viable a candidate for dark matter as sparticles”
Wilczek “If not axions, please tell me how to solve the Strong-CP problem”
Witten “Axions may be intrinsic to the structure of string theory”

Axions and Axion-like particles

- Axion mass related to the pion mass: $m_a \sim m_\pi f_\pi / f_a = \dfrac{0.60\ \text{meV}}{f_A/10^{10}\ \text{GeV}}$
- Axions couple to two photons

Photon coupling	$L_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F} a = g_{a\gamma} \vec{E} \cdot \vec{B}\, a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$



Raffelt

- An *axion-like-particle* (ALP) is a more general particle that can arise from either a pseudoscalar or scalar field, ϕ, and no longer has the connection to the pion.

pseudoscalar

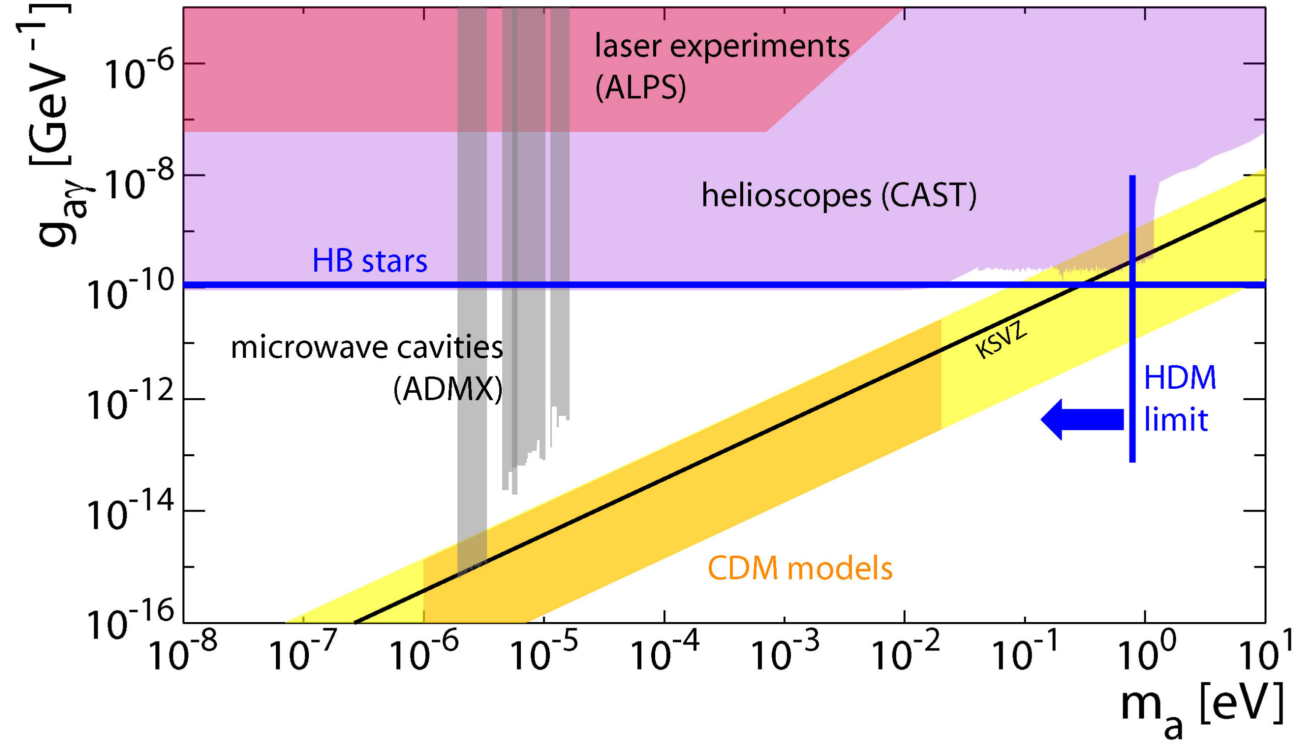
$$\mathcal{L}_{\text{int}} = -\frac{1}{4}\frac{\phi}{M} F_{\mu\nu}\widetilde{F}^{\mu\nu} = \frac{\phi}{M}(\vec{E} \cdot \vec{B})$$

scalar

$$\mathcal{L}_{\text{int}} = -\frac{1}{4}\frac{\phi}{M} F_{\mu\nu}F^{\mu\nu} = \frac{\phi}{M}(\vec{E} \cdot \vec{E} - \vec{B} \cdot \vec{B})$$

Current constraints

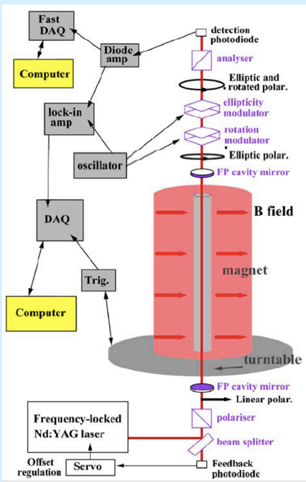
- Axion and ALP parameters are constrained by astrophysical and experimental measurements
  - Stars don't burn out and hot dark mater not likely.
  - Laser, microwave cavity, solar telescopes (helioscopes) are a <u>partial list</u> of techniques that provide experimental bounds.



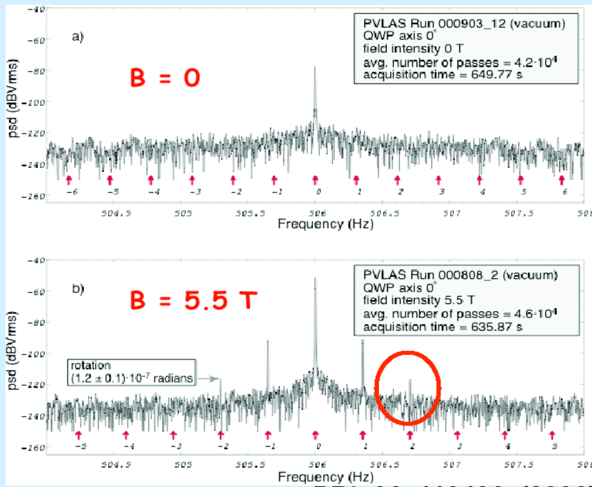
M Pivovaroff

Intriguing observation

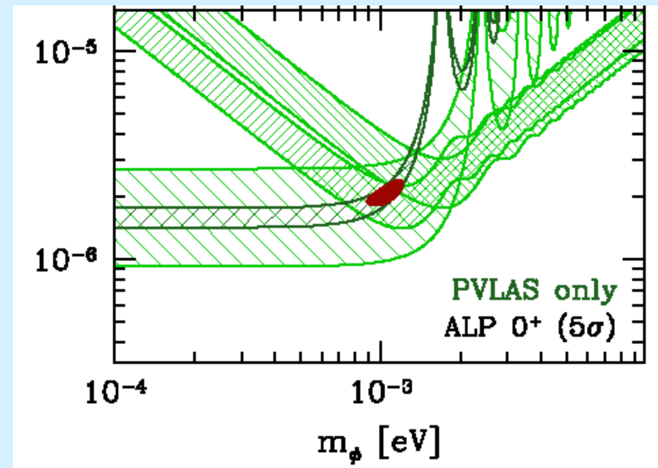
2006: spurious signal in an experiment looking to study polarization of the vacuum – theoretical ways to evade limits



PVLAS

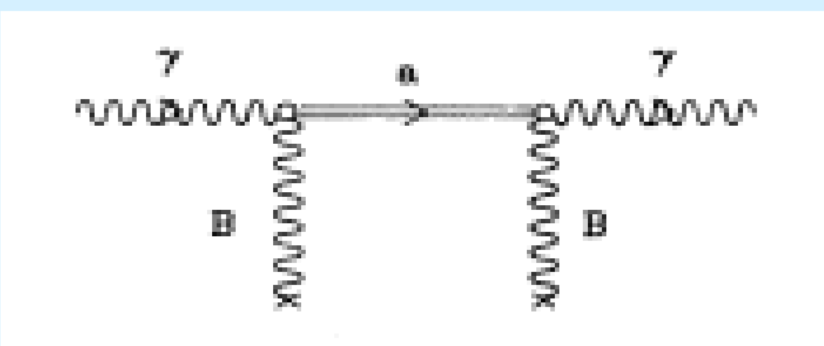


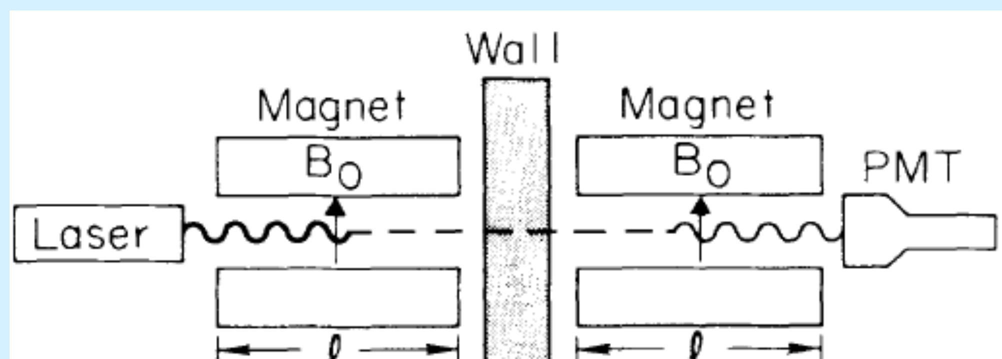
PRL 96, 110406, (2006)



Ringwald et al.

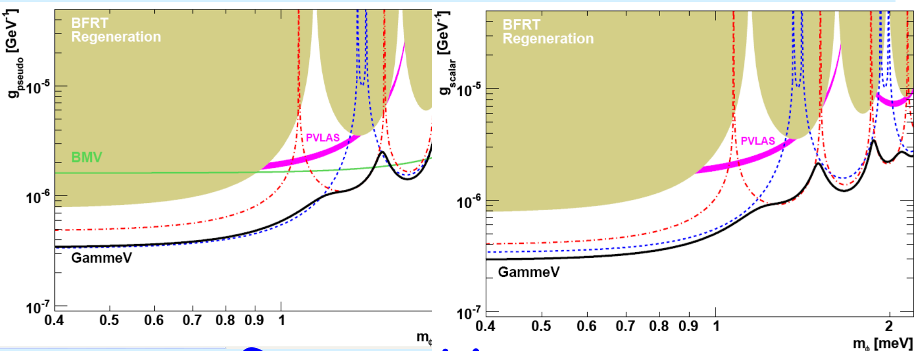
Redo a “Light shining through a wall” experiment

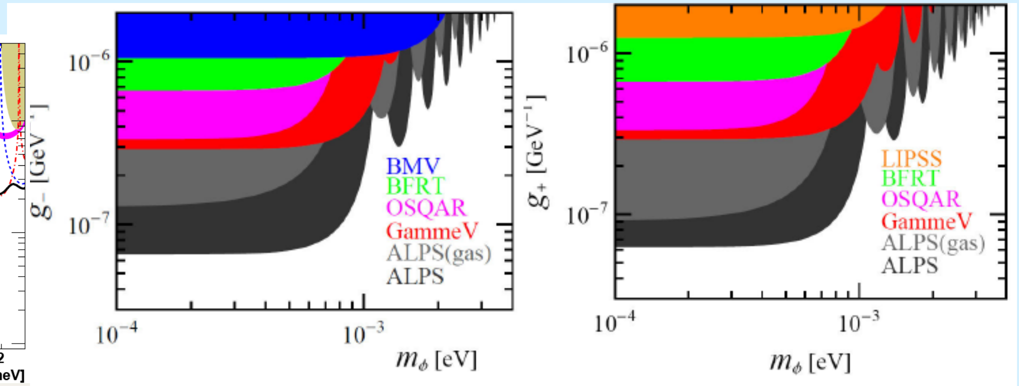




K. Van Bibber, et. al., PRL 59, 759 (1987)

World-wide effort



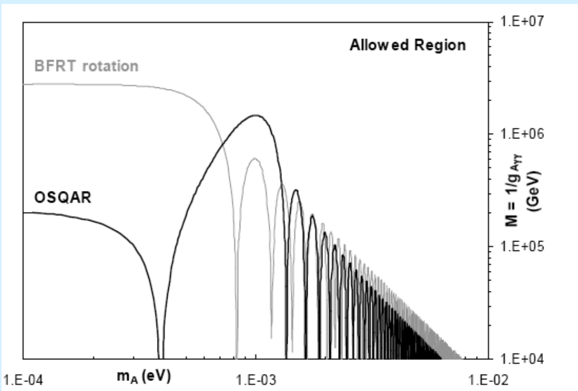


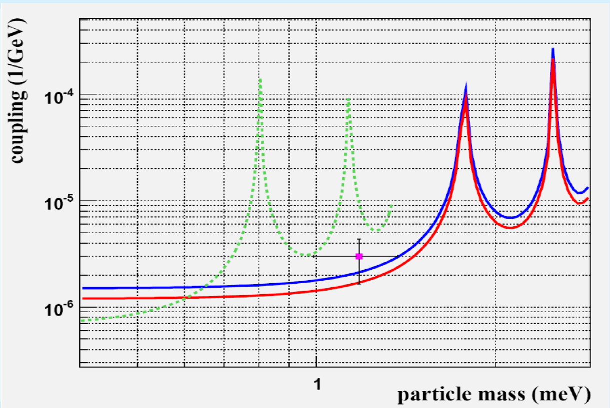
GammeV @FNAL

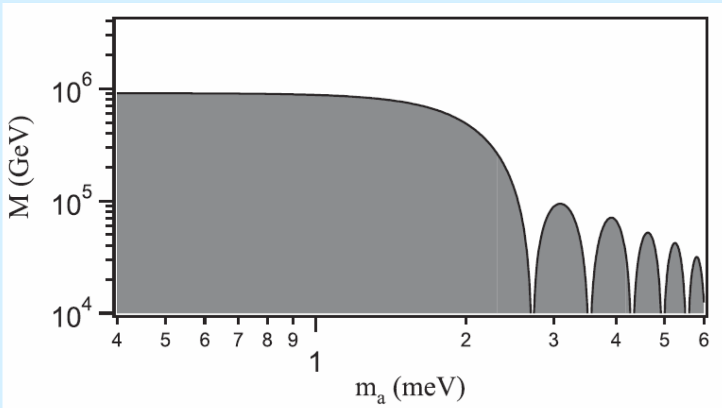
PRL **100**, 080402 (2008)

ALPS @DESY

PLB 689, **149** (2010)







OSQAR @CERN

PRD **78**, 092003 (2008)
Note: with N_2 gas

LIPSS @JLab

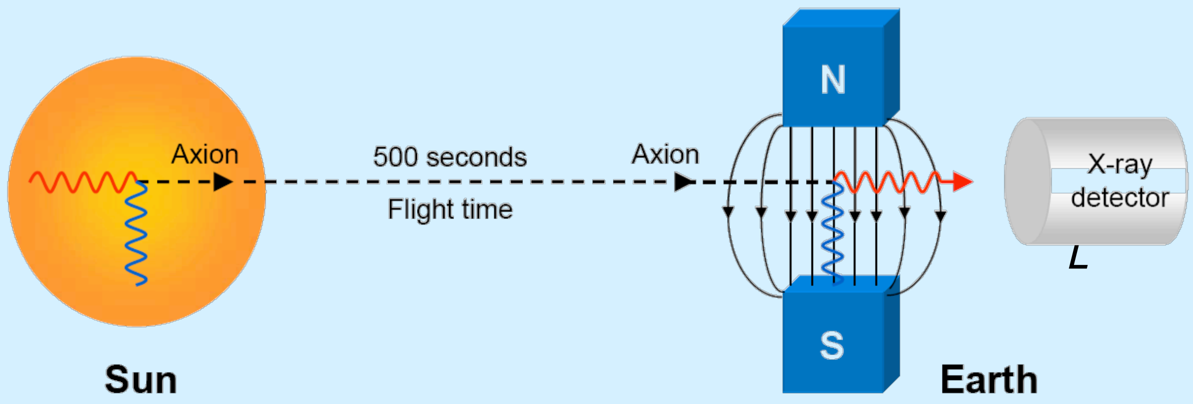
scalar only
PRL **101**, 120401(2008)

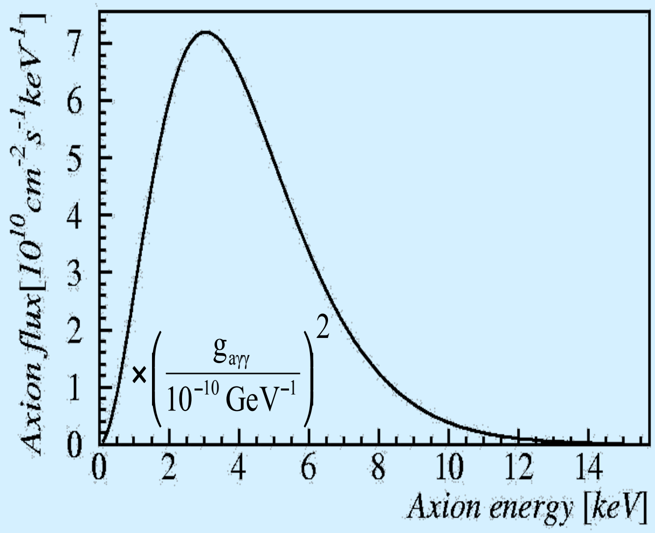
BMV @France

pseudoscalar only
1st results: PRL **99**, 190403 (2007)
Final results: PRD **78**, 032013 (2008)

CAST Experiment

- CERN Axion Solar Telescope





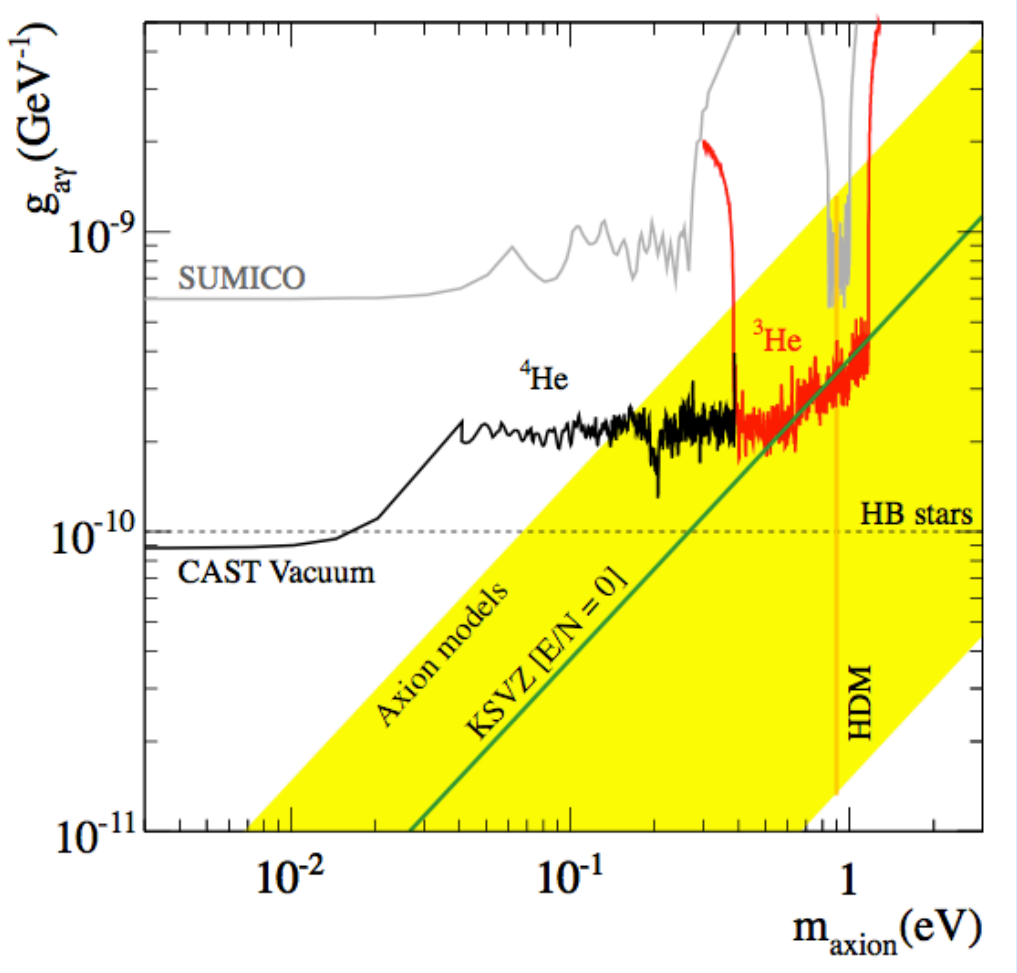
Point LHC dipole toward the sun.
Detect possible X-rays from axion reconversion.

CAST

CAST Results

2007 limits in vacuum
$< 0.88 \times 10^{-10}$ GeV^{-1}

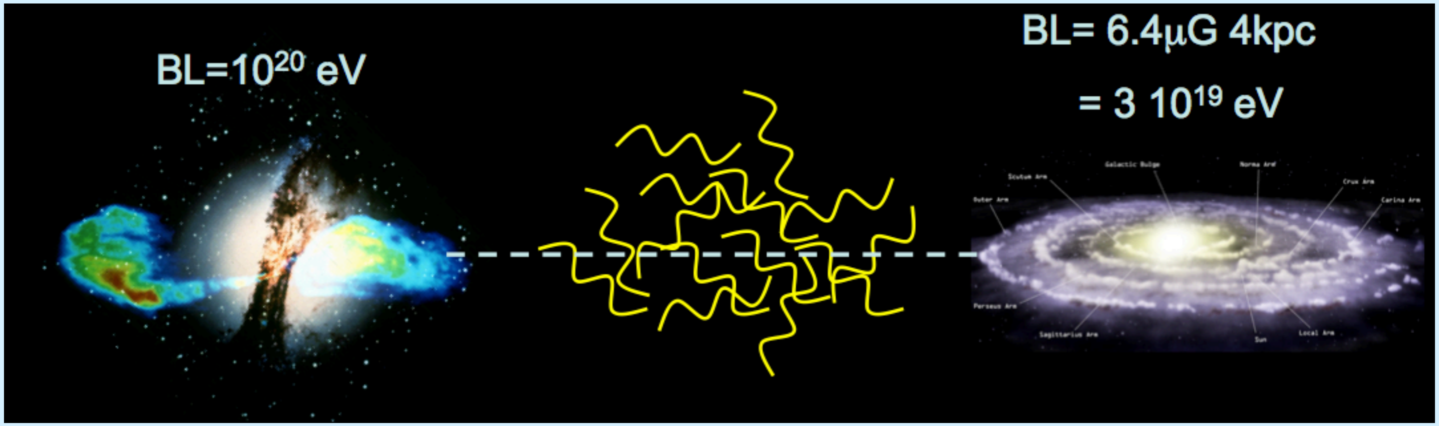
Coherence lost at large m_a. Program 2009-2011 to use buffer gasses to give an effective photon mass that can be scanned versus gas pressure.



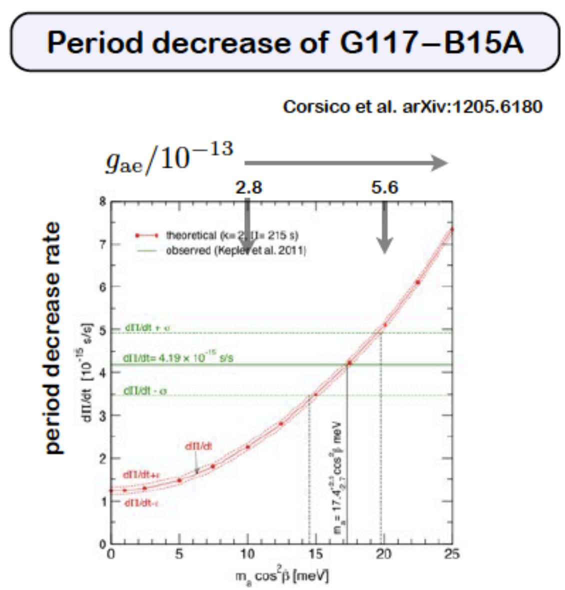
CAST, arXiv:1307.1985 [hep-ex]

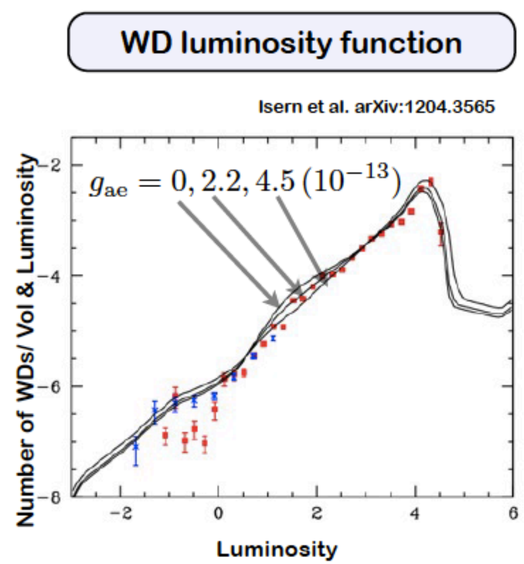
Motivation for $g_{\alpha\gamma\gamma} \sim 10^{-(11ish)}$

Anomalous observation of high energy gamma rays

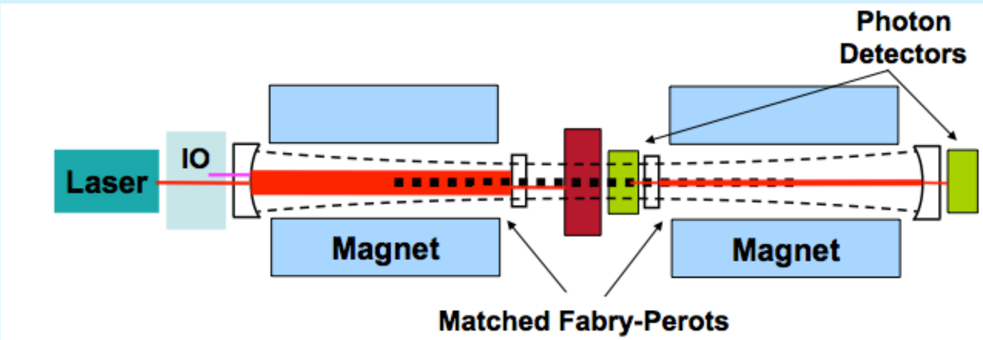


Hints of anomalous cooling of white dwarf stars





Next generation light shining through walls



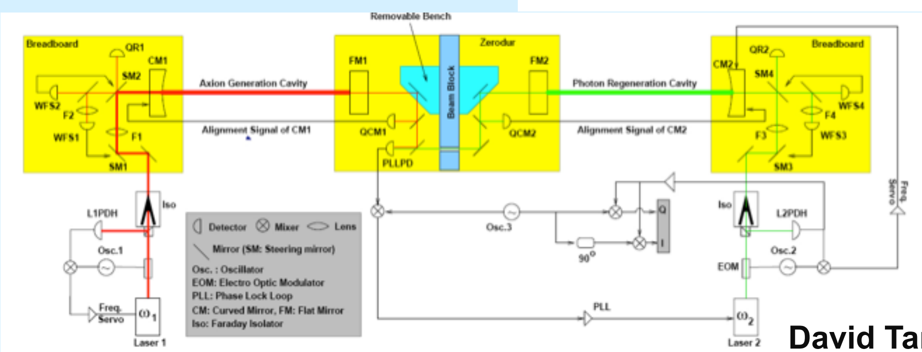
Matched optical cavities on both sides of the wall give an enhancement of $\mathcal{FF}$ (finesse)

F. Hoogeveen and T. Ziegenhagen, Nucl. Phys. B **358**, 3 (1991)
Mueller, Sikivie, Tanner, van Bibber, Phys. Rev. D **80**, 072004 (2009)
Phys. Rev. Lett. **98**, 172002 (2007)

ALPS-II DESY approved first stages towards ALPS-II

Axel Linder

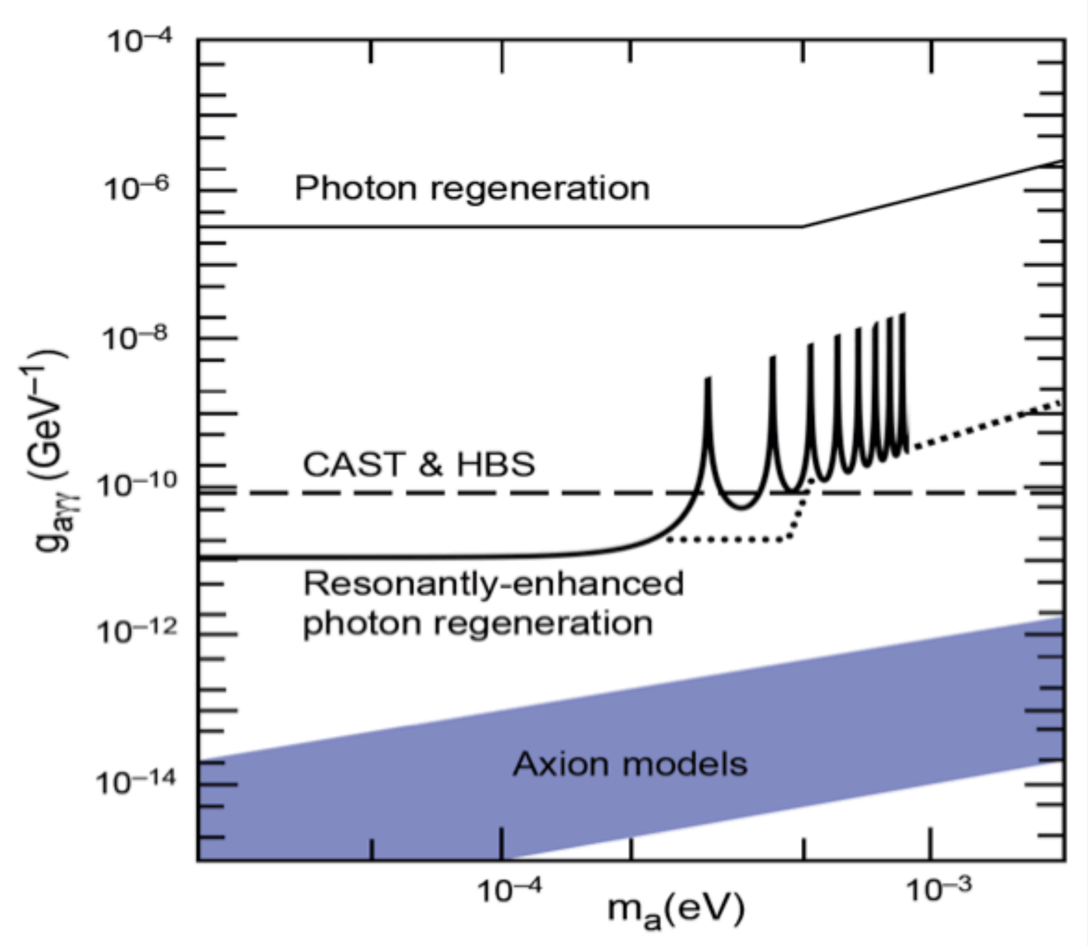
Parameter	Scaling	ALPS-I	ALPS-IIc	Sens. gain
Effective laser power $P_{\rm laser}$	$g_{a\gamma} \propto P_{\rm laser}^{-1/4}$	1 kW	150 kW	3.5
Rel. photon number flux n_γ	$g_{a\gamma} \propto n_\gamma^{-1/4}$	1 (532 nm)	2 (1064 nm)	1.2
Power built up in RC $P_{\rm RC}$	$g_{a\gamma} \propto P_{reg}^{-1/4}$	1	40,000	14
BL (before& after the wall)	$g_{a\gamma} \propto (BL)^{-1}$	22 Tm	468 Tm	21
Detector efficiency QE	$g_{a\gamma} \propto QE^{-1/4}$	0.9	0.75	0.96
Detector noise DC	$g_{a\gamma} \propto DC^{1/8}$	0.0018 s^{-1}	0.000001 s^{-1}	2.6
Combined improvements				3082



David Tanner

REAPR – US effort (Univ of Florida and Fermilab, etc.) submitting R&D proposals. Related laser expt's at FNAL.

Possible reach



Cost driven by laboratory support of operating a long string of super-conducting magnets.

DESY: HERA magnets
FNAL: Tevatron "

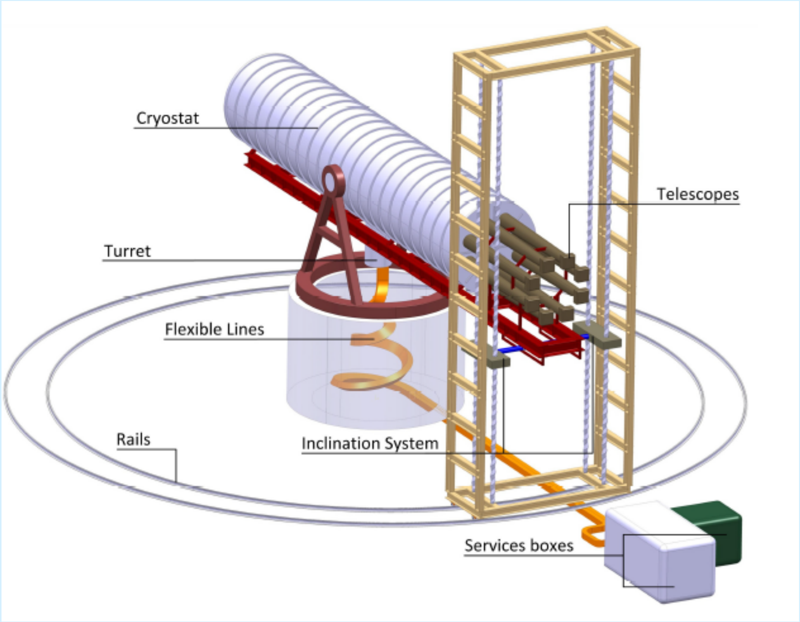
Baseline design with BL=180 Tesla-meters, with F=3 10^5 , P=10W, Integration time T=30 days.

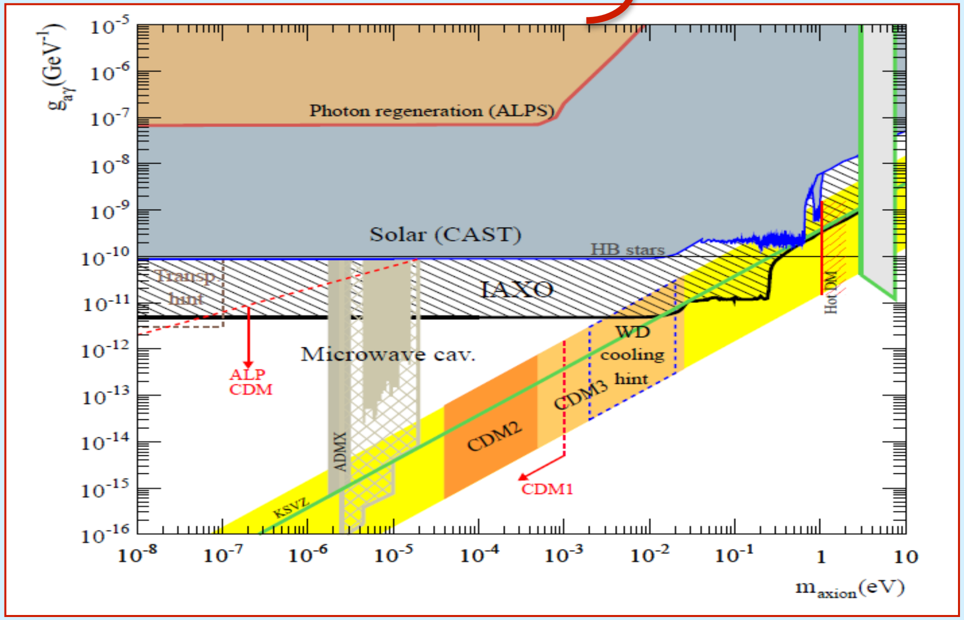
IAXO
International axion x-ray observatory

- Collaboration formed and growing
  - 100 physicists, 20 institutions, 15 countries
- Conceptual design report in preparation; LOI solicited by CERN and **submitted August 2013**
- 4th gen helioscope supported in 2011 ASPERA roadmap
- Socializing IAXO with DOE/SC/HEP and communities of interest (dark matter, particle astrophysics, …)
- Budget [ROM] = $60−110M (dependent on cost models)
  - $30M magnet
  - $10M CF
  - $16M optics
  - $ 6M detectors

does not include labor

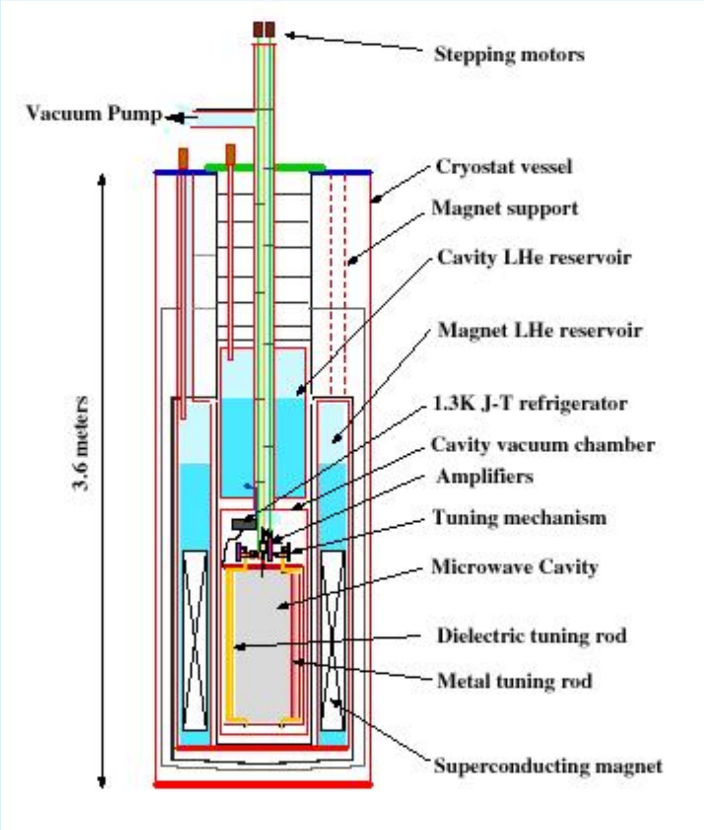
J. Vogel

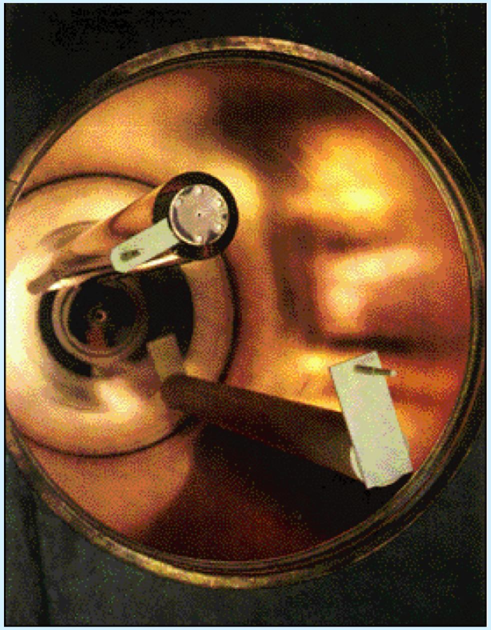




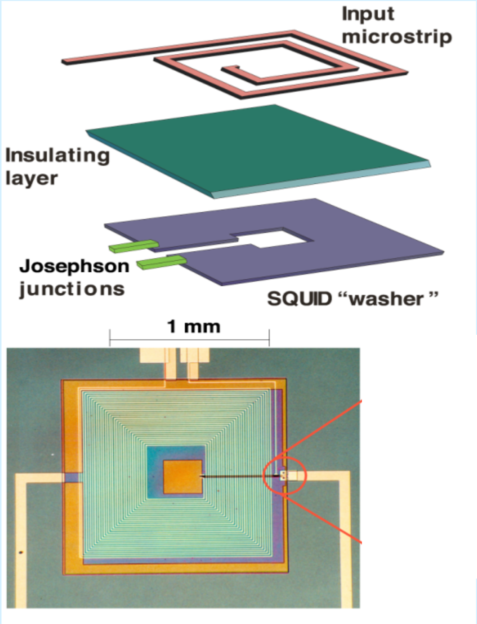
ADMX Experiment

- Axion Dark Matter Experiment
  - Tunable microwave cavity in B field looking for dark matter axions converting into a detectable photons.





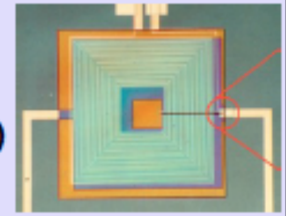
High Q cavity



SQUID for receiver

ADMX

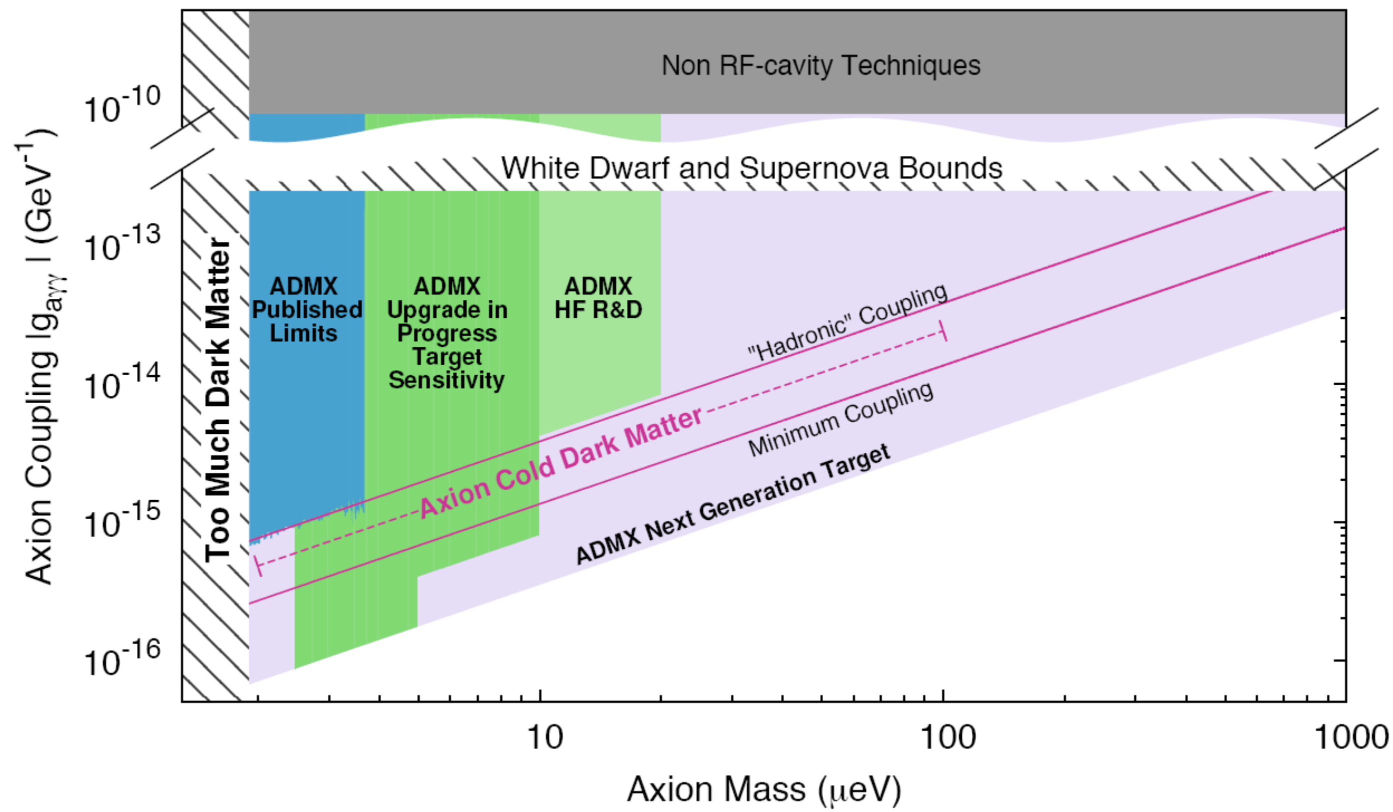
ADMX Results and Future

Stage	Phase 0	Phase I	Phase II
Technology	HEMT; Pumped LHe 	Replace w. SQUID 	Add Dilution Fridge 

Phase I at LLNL published

Phase II being installed at U of Wash

R&D ongoing for ADMX-HF



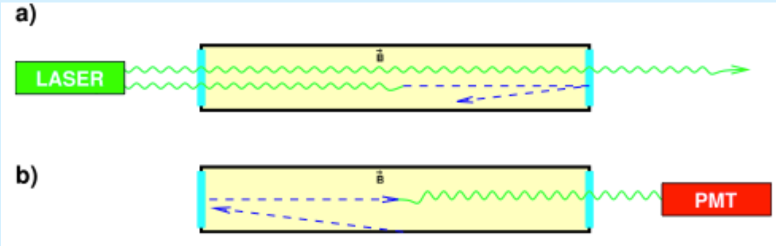
Chameleons

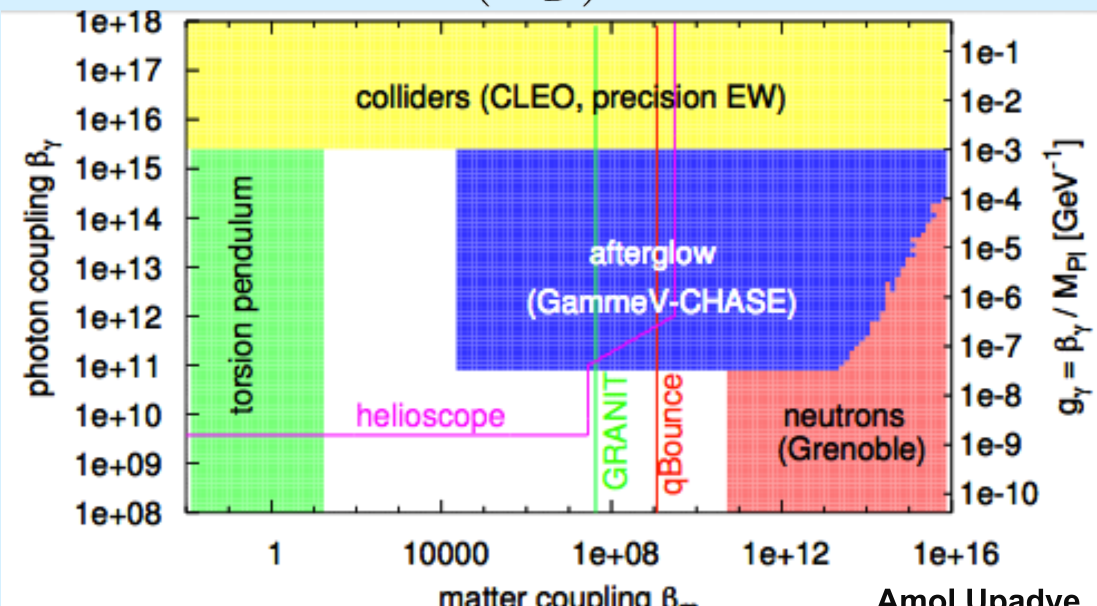
A Chameleon is a particle whose properties depend on it's environment. At low mass density the chameleon is light, and acquires a large effective mass in high mass density.

➔ A possible dark energy particle

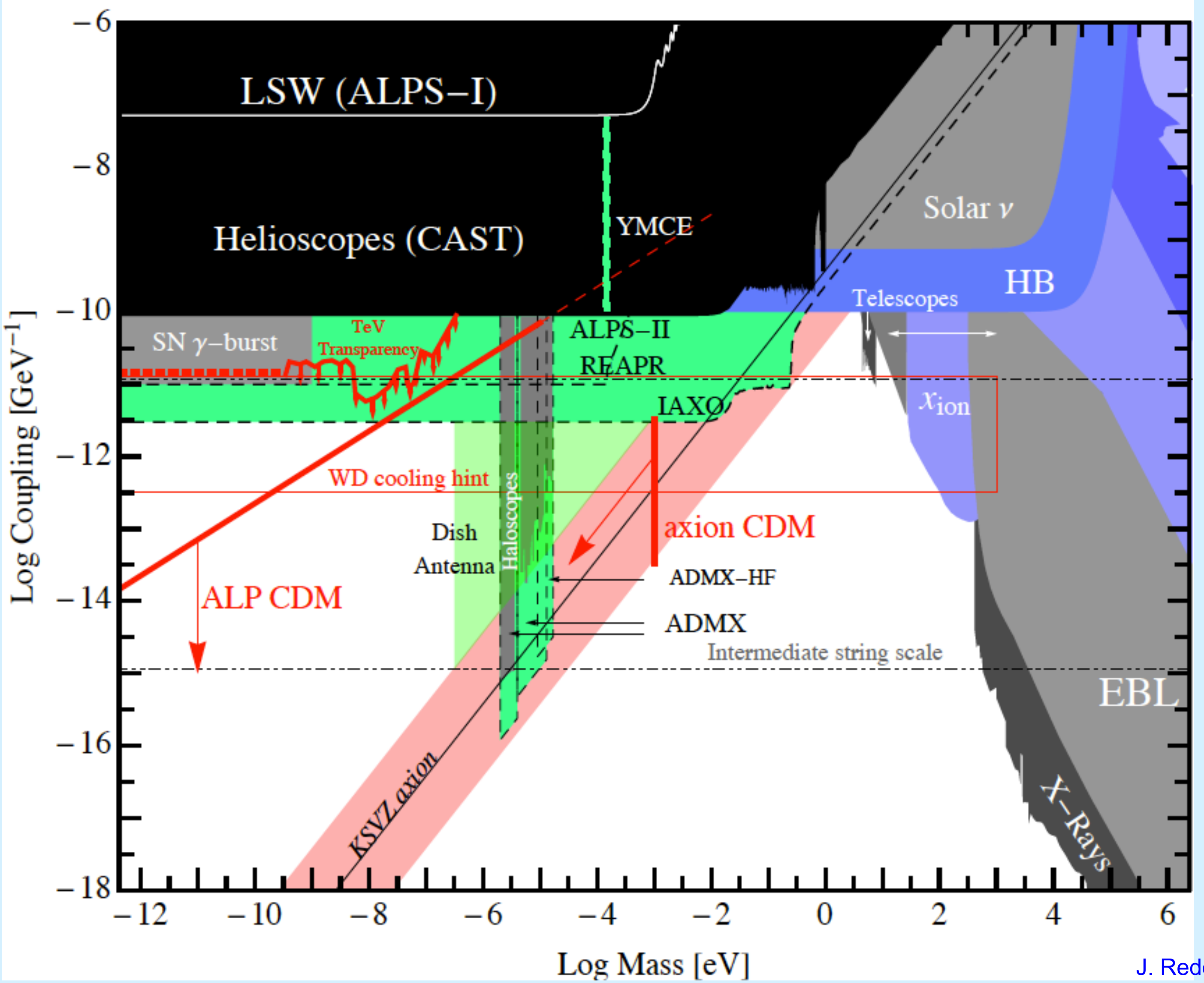
➔ Afterglow experiment is one test

$$\mathcal{L}_{\rm int} = -V(\phi) + \exp\left(\frac{\phi}{M_D}\right) g_{\mu\nu}T^{\mu\nu} - \frac{1}{4}\frac{\phi}{M}F_{\mu\nu}F^{\mu\nu}$$





Axion-like particle parameter space



J. Redondo, A. Ringwald, et al.

Points for HEP Community

- New light weakly-coupled particles
  - Strongly motivated theoretically
  - Hints from astrophysical observations
  - The Intensity Frontier approach provides a means to directly produce new particles and explore New Physics at low energy
  - Energetic subfield of particle physics with world-wide interest
  - Opportunities are quite extensive, sometimes limited by imagination, and represent a low cost means towards high impact discovery physics!